OVERVIEW OF EUROPA'S ICY SHELL: QUESTIONS OF THICKNESS, COMPOSITION, RHEOLOGY, TECTONICS, AND ASTROBIOLOGICAL POTENTIAL. William B. McKinnon, Dept. of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130, mckinnon@wustl.edu.

Introduction: Europa possesses an icy shell; this much has been clear since *Voyager*. That Europa's shell is also floating is now generally accepted as well, thanks to *Galileo*. Much attention has been focused on determining the thickness of the shell, but as a goal in itself this is not enough! We also need to know what the shell is made of, what its rheological, mechanical, & structural properties are, how these govern and respond to tectonic forces and impacts, how the shell has evolved through geologic time, and what, if any, astrobiological potential the shell and ocean below possess.

Some Historical Perspective: Why is Europa's icy shell thought to be "ungrounded?" Four close passes by *Galileo* determined Europa's second-degree gravity term C_{22}, which in turn yielded a normalized moment-of-inertia (MOI) of 0.346 ± 0.005 ($1\ \sigma$) [1]. This MOI *assumes* that the tidal and hydrostatic figure is hydrostatic. Nevertheless, even factoring in generous systematic uncertainty, the MOI implies a differentiated Europa, and for cosmochemically plausible rock+metal compositions, a deep ice (and/or water) layer [1,2]. For solar rock+metal, the icy layer is ~135 km thick [3].

The induced magnetic field clearly indicates a conducting layer within or close to Europa. Because the ionosphere of Europa is insufficiently conductive to carry the required currents, the conductive layer must be within the body of Europa [4]. A metallic core is too deep to account for the magnitude of the induced field, so the conducting layer must lie within the icy shell or outermost mantle. Barring an exotic composition for the latter, Europa must possess a conductive ocean beneath the ice or sufficiently hot outer mantle that an ocean, conductive or not, is implied [2,4].

The gravity and magnetic data rule out earlier hypotheses for a thin (≤25-km) solid ice shell directly coupled to a hydrated silicate interior [e.g., 5]. In this concept Europa's lineaments were due to stresses arisng from convection in the rocky interior and propagated upward into the ice. This is not to cast aspersions on historical models but to point out that such thinking represented a barrier to accepting or even considering a "mobilist" Europa [e.g., 6]. The lesson for today is not to become so enamored of one's own preferred hypotheses for Europa's icy shell (e.g., "thick" vs. "thin") that one cannot see the logic and value of alternatives.

Composition: Europa's shell is mostly water ice, but there are other components, especially in areas of recent tectonic activity or impact exhumation. The near-infrared absorption bands are distorted in a manner characteristic of highly hydrated sulfates. Radiation processed $MgSO_4{\bullet}nH_2O$ is arguably the leading candidate [2], but an alternative is $H_2SO_4{\bullet}nH_2O$ [7]. In the latter case, the sulfur could be exogenic (Iogenic) in origin. Exospheric Na and K are seen as well, and in a ratio that implies they are not dominantly Iogenic [7], but the source minerals on Europa (presumably chlorides and/or sulfates) have not been identified.

The composition of the ice shell reflects the composition of the ocean below, albeit after geophysical and radiolytic processing. Theoretical models favor an oxidized, sulfate-bearing ocean [8-10] with low (compared with terrestrial) concentrations of alkali salts [8,9]. Europa's *primordial* ocean, however, was most likely reduced and sulfidic and only later evolved to be oxidized and modestly sulfate bearing [10]; this is in strong contrast to the hypersaline (~saturated) CI-analogue model [8]. The conductivity limits implied by the Galileo magnetometer data unfortunately do not provide useful constraints on sulfate concentration. For ocean depths consistent with the gravity data, the minimum conductivity necessary to account for the induced field is ~0.1 S m^{-1}, which is ~1/25 that of terrestrial seawater [2,4]. The implied NaCl salinity scales accordingly, and can be met by even the partial extraction model of [9]. In this case the minimum sulfate concentration needed is zero. If the conductivity is due to sulfate alone, ~1 wt% is the minimum implied.

Improved spectral analyses, either from existing or future data, will be critical to progress. For although the thermomechanical properties (diffusivity, viscosity, etc.) of pure water ice are very well understood, those of highly hydrated sulfate salts (for example) are not, and are likely quite different from those of water ice (owing to, among other things, the large unit cells of the sulfate minerals [11]).

Rheology: Experimental studies have made such progress that a fairly complete understanding of the steady-state viscous creep of pure water ice exists [12,13]. For most temperature and stress regimes of interest for Europan geology, nearly Newtonian grain-size-sensitive GBS creep (GSS in [13]) is the dominant flow law. Only for higher stress levels and larger grain sizes (>1 cm) is power-law creep law dominant (see deformation maps in [13]). For very fine grain sizes and very low stresses, diffusional creep may become important [12], but such creep has yet to be observed experimentally. Given the importance of grain size (d), a good understanding of what controls grain growth under planetary conditions is necessary [13]. Largely untapped glaciological understanding should help, notwithstanding current rheological controversies [14].

Tectonics: *To convect or not to convect?* Using a tidally linearized GBS rheology and the convection theory of Solomatov and coworkers, Europa's shell was shown to be unstable to convection for shell thicknesses >20 km or so (for d = 1 mm), with thinner shells unstable for smaller grain sizes (>10 km or so for d = 100 μm) [15]. Using an older, generic Newtonian rheology and a modified parameterized convection scheme, [16] argued that Europa's shell is less likely to convect (i.e., the shell must be thicker in comparison with [15]). As [15,16] both treat the shell as bottom heated, the difference in results stems from the rheologies and convection formalisms employed.

Tidal heating is a harsh mistress. There are two different problems, when does convection initiate (~bottom heated) and what is the steady-state condition (~internally heated)? In the latter case, tidal heating is important in the convecting sublayer but may be neglected (with care) in the stagnant lid [16-18], which differs from standard treatments of internally heated convection. Using tidally linearized rheologies and a modified parameterized convection scheme for internal heating, [17] found steady-state solutions with shell thicknesses ranging from ~50 km (GBS & d = 0.1 mm) to ~15-20 km (GBS & d = 1 mm as well as power-law ductile A [13]). They favored the high heat flows from the GBS & d = 1 mm case on geological grounds, but it is notable that a steady-state solution for ductile A creep dominance was found with a substantially thinner shell than stability (initiation) conditions indicate [15,17]. This either implies that the evolution of the shell when convection begins is quite interesting (it thins) or, of course, that more analysis is necessary.

It has been hypothesized that grain-size evolution in hot, straining ice will lead to ~equal contributions from GBS and power-law creep [13]. For present-day tidal amplitudes, this implies $d \sim 1$ mm and basal viscosities near 10^{14} Pa-s [15]. These conditions are very close to those for maximum tidal heating in the sublayer [15,17]. Is there a "Europanthropic" principle?

Pits and uplifts. Numerous uplifts, breached uplifts, regular and irregular domes, small chaos regions, and apparently genetically related depressions (pits) are seen across Europa, ranging in size from the very large Murias Chaos [19] to features no more than a few km across [e.g., 20]. The structural relations clearly indicate a dominant role for solid-state diapirism [19,21] and for the pits volume loss due to subsurface melting [22]. Features the scale of Murias may be due to upwelling in an ice shell marginally unstable to convection [23]. The far more numerous, small scale features are more likely due to diapiric instability in a bottom thermal boundary layer (the traditional source of plumes in the terrestrial planets). The smallest uplifts imply the smallest diapirs, which imply a bottom boundary layer thickness of ~1 km or less [18]. For such a thin layer to be unstable requires a low viscosity, which in [18] is due to diffusional creep at very fine grain sizes (~20-60 μm). Alternatively, tidally linearized GBS creep at similar grain sizes will suffice, especially if weakened by grain-boundary melting [14]. Are such grain sizes possible for hot ice? Perhaps impurities from the ocean impede grain growth, or perhaps convective strain fines grain size after all [15].

At minimum, existence of the boundary layer provides evidence for (and constrains) core heat flow. The ability of small diapirs to rise a sufficient distance through the sublayer has been questioned [20] based on [24]. Getting diapirs to pierce the stagnant lid and elastic lithosphere is the real problem. Ascent may be aided by tidal heating [15,25], low viscosity due to partial melt or low grain size, or compositional effects (melting and drainage of brine) [18,26].

Cycloid ridges. The evolution of cycloid ridges from cycloid cracks, and the diurnal stress cycle needed to generate them, are powerful geologic arguments for a floating ice shell [2,27]. Movement on deep (>1 km) faults at 0.1 MPa stresses remains problematic, however. These and other aspects of shell tectonics will be discussed as time allows.

References: [1] Schubert G. et al. (2004) in *Jupiter – Planet, Satellites & Magnetosphere,* Cambridge Univ. Press, in press. [2] Greeley R. et al. (2004) in *Jupiter–PS&M,* CUP, in press. [3] McKinnon W.B. and Desai S.S. (2003) *LPS XXXIV*, #2104. [4] Zimmer C. et al. (2000) *Icarus, 147,* 329-347. [5] Ransford G.A. et al. (1981) *Nature, 289*, 21-24. [6] Schenk P.M. and McKinnon W.B. (1989) *Icarus, 79*, 75-100. [7] Johnson R.E. et al. (2004) in *Jupiter–PS&M,* CUP, in press. [8] Kargel J.S. et al. (2000) *Icarus, 148*, 226-265. [9] Zolotov, M.Y. and Shock E.L. (2001) *JGR, 106*, 32,815-32,827. [10] McKinnon W.B. and Zolensky M.E. (2003) *Astrobiology, 3*, in press. [11] Hawthorne F.C., et al. (2000) *Rev. Min. Geochem., 40*, 1-112. [12] Goldsby D.L. and Kohlstedt D.L. (2001) *JGR, 106*, 11,017-11,030. [13] Durham W.B. and Stern L.A. (2001) *AREPS, 29*, 295-330. [14] Goldsby D.L. and Kohlstedt D.L. (2002) *JGR, 107(B11)*, ECV-17. [15] McKinnon W.B. (1999) *GRL, 26*, 951-954. [16] Hussmann H. et al.. (2002) *Icarus, 156*, 143-151. [17] Ruiz J. and Tejero R. (2003) *Icarus, 162*, 362-373. [18] Nimmo F. and Manga M. (2002) *GRL, 29(23),* 24. [19] Figueredo, P.H. et al. (2002) *JGR, 107(E5),* 2. [20] Greenberg R. et al. (2003) *Icarus, 161,* 102-126. [21] Pappalardo, R.T. et al. (1998) *Nature, 391,* 365-368. [22] McKinnon W.B. and Schenk P.M. (2004), in prep. [23] McKinnon W.B. and Gurnis M. (1999) *LPS XXX*, #2058. [24] Rathbun J.A. et al. (1998) *GRL, 25*, 4157-4160. [25] Sotin C. et al. (2002) *GRL, 29(8)*, 74. [26] Pappalardo, R.T. and Barr A.C. (2003), submitted. [27] Hoppa et al. (1999) *Science, 285*, 1899-1902.